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The problem of lead poisoning needs little introduction to conservationists concerned about dwindling populations of wild waterfowl and the perpetuation of wildfowling. For more than a century, it has been known that waterfowl will die after ingesting lead shot picked up from the bottoms of shallow lakes, ponds, and marshes. Major losses have been well documented for nearly four decades, but most waterfowl that die from lead poisoning are probably never noted. The annual mortality due to this malady is difficult to estimate but may amount to a wastage of nearly a million North American ducks, geese, and swans in some years. Most of these birds succumb after the hunting season and represent a loss of potential breeders. The possibility for increased losses mounts, as some 6,000 tons of spent shot are deposited on waterfowl habitat each year. Fortunately, most shot settles in deep water or soft bottoms out of the reach of waterfowl; but much accumulates on hard, shallow bottoms of our diminishing wetlands.

The need for a solution to the lead poisoning problem has been recognized by both conservationists and the ammunition industry for many years. As early as 1936 there was an attempt to solve the problem by making a shot of lead-magnesium alloy that would disintegrate in water. In the early 1950's, a study launched by the Illinois Natural History Survey and supported by the Olin Mathieson Chemical Corporation resulted in a bulletin by Frank C. Bellrose (1959) entitled, "Lead poisoning as a mortality factor in waterfowl populations." Bellrose not only provided a thorough analysis of the problem but pioneered in the search for a solution. He concluded that the solution depended on development of a non-toxic substitute for lead shot. One of several candidates that he tested was an annealed iron shot produced by Olin Mathieson under a proprietary process. That process was not feasible for large-scale production, and the laboratory which developed it is no longer in existence. However, Bellrose conducted some limited shooting tests with iron shot produced by the process and found that it was almost as effective as lead shot at ranges up to 50 yards. He concluded: "Should lead poisoning become a more serious menace to waterfowl populations, iron shot provides a possible means of overcoming it."

Several years later, the Mississippi Flyway Council (1965) recommended an action program to reduce waste in waterfowl populations and thereby make more birds available for recreation. The lead poisoning problem was given top priority and received an updated review in the publication, *Wasted Waterfowl*. Included in that report were the results of a comparative field testing of iron and lead shot. The test indicated that Number 2 iron shot would kill ducks as readily as Number 4 lead shot at ranges up to 40 yards and might result in fewer cripples.

In the fall of 1966, the Sporting Arms and Ammunition Manufacturers' Institute (SAAMI) and the Bureau of Sport Fisheries and Wildlife initiated a cooperative research effort to solve the vexing problem of waterfowl poisoning caused by ingested lead shot. SAAMI financed a $100,000, 2-year study by the Illinois Institute of Technology (IIT)—one of the nation's outstanding technical research organizations—to find and develop a suitable substitute for lead shot. Promising candidates were to be tested for possible toxic effects by the Bureau's Patuxent Wildlife Research Center. Efforts by IIT to render lead nontoxic with biochemical additives were unsuccessful, and a thorough review of lead alloys, protective coatings, and disintegrating shot also proved unproductive. Again, the only promising candidate was soft iron.

Despite the fact that iron is the nearest practical substitute for lead, it has been considered a rather poor replacement because of certain inadequacies. As Baker (1966) pointed out, lead is well suited for shot-making in all respects except toxicity. It has the high density needed for maximum velocity and energy retention; is relatively low in cost; is easily processed; is soft enough to preclude damage to gun barrels and chokes; and is relatively inert. Iron has a density of 0.28 lbs./cu. in. as compared to 0.41 lbs./cu. in. for lead. Iron is inexpensive in its raw form, but processing costs are high, and shot produced from it are normally so hard that gun barrels and chokes are damaged. Protective liners or coated shot can minimize barrel scratching, but choke deformation still occurs. Softness can be achieved by repeated annealing, but this increases the cost. Above all, however, iron has been considered a poor substitute because its low density would presumably result in performance shortcomings—particularly at ranges of more than 40 yards.

When the research of IIT indicated that soft iron shot was the best remaining substitute, plans were made for a thorough testing of the capability of iron to kill ducks at various distances. Engineers from SAAMI and biologists from the Patuxent Wildlife Research Center cooperatively designed and constructed a shooting facility and testing program to compare the killing efficiencies of various shot loads under carefully controlled conditions.

This paper summarizes the principal findings of that testing program.

METHODS AND MATERIALS

Guns and ammunition for the test were provided by SAAMI. A 12-gauge pump shotgun with 30-inch, full choke barrel was used. Additional barrels were provided and used during the test. These barrels were pretested to determine their pattern performance, and each barrel was retired after a prescribed amount of firing. Commercial 12-gauge 2¾" 1¼ ounce lead loads in Number 4 and Number 6 shot sizes were used as standards for comparison.

The ammunition industry produced 1000 pounds of Number 4 iron shot from low carbon, super-soft wire, utilizing a process that produces air-rifle shot. Due to work hardness, the shot were subsequently annealed to provide a nominal external hardness of 65 DPH. This was soft enough to preclude the excessive barrel damage experienced with other iron shot although ultimate choke damage was not entirely prevented. The ammunition industry provided loaded rounds which would deliver the best possible performance. These maximum-weight, 1-ounce iron loads contained about 180 pellets, the same number as the 1¼-ounce loads of Number 4 lead shot. The 1¼-ounce loads of Number 6 lead shot averaged about 300 pellets. The iron shot were surrounded by a polyethylene liner 0.020 inches thick to provide added protection to the barrel. A slow-burning ball powder provided maximum muzzle velocity.

A unique duck-transport device was engineered by the ammunition industry and constructed at the Patuxent Wildlife Research Center. This automated shooting device moved a tethered, wing-flapping duck across a point where the mounted, preaimed gun fired a "perfect" shot. The system consisted of a cable-pulled carriage on a 75-ft. set of tracks. An electric motor, through gear reduction and clutch-brake units, accelerated the carriage to about 20 mph at the shooting position. Ducks were tethered to an adjustable rod mounted on the carriage and shaped as an inverted "J". A close simulation of a free-flying duck, passing a shooting position, was achieved. The shotgun was mounted on a movable wooden "horse" and triggered by a solenoid activated through a microswitch. Other microswitches braked the carriage on forward and return trips. A movable control box for the entire facility was positioned beside the gun mount. Sighting stakes were erected for each shooting distance so that the gun could be accurately aimed prior to each shot. Standard 30-inch targets were shot to locate center of patterns and determine positions of sighting stakes. The targets were also used to assure that ducks were centered in the pattern prior to each day of shooting.

Game-farm mallards of uniform age and closely similar to wild birds in appearance and weight were used for this test. Equal numbers of drakes and hens were individually weighed and banded.

The experiment utilized a split plot design wherein shooting distances comprised the whole plots, and combinations of shot types and sex, arranged factorially, comprised the subplots. Ducks were shot in sets of five for a given combination of factors. The initial test design called for 900 ducks to be shot at ranges of 30, 40, and 50 yards. When it became evident that all shot loads were extremely effective at 30 yards and that iron performed well at 50 yards, the 30-yard position was discontinued and a 60-yard position was added. The ducks in that test were shot from a broadside position and an elevation angle of about 15°. Subsequently, 300 more ducks were shot from a nearly head-on direction at ranges of 40 and 50 yards. The testing was started in March, 1968, and concluded in June. After the results were tabulated and examined, additional data for intermediate distances seemed desirable; therefore, a supplementary test at ranges of 45, 55, and 65 yards was conducted in November-December, 1968. The results of these three tests are summarized together in the accompanying tables, although they have been evaluated statistically as separate entities.

The fate of each duck was recorded either in one of four kill categories or as a survivor. The kill categories were: (1) instant (within 1 minute), (2) 1 minute to 5 minutes, (3) 5 minutes to 1 day, and (4) 1 day to 10 days. All ducks alive at the end of a shooting day were held for 10 days in pens with food and water. Those alive after 10 days were killed with carbon monoxide. All carcasses were weighed, examined for broken wing and leg bones and fluoroscoped to obtain counts of embedded shot. A representative sample of ducks (630) was defeathered to obtain counts of entrance and exit wounds.

RESULTS

Table 1 depicts the results in categories which are based on timed intervals after shooting. These categories provide an objective basis for comparing the killing effectiveness of the three shot types. However, they cannot be directly translated to hunting success in the field, where a duck is either bagged, crippled and lost, or "missed."

TABLE 1.—KILLING EFFICIENCIES OF THREE SHOT TYPES EXPRESSED AS PERCENTAGES OF DUCKS IN TIMED KILL CATEGORIES.

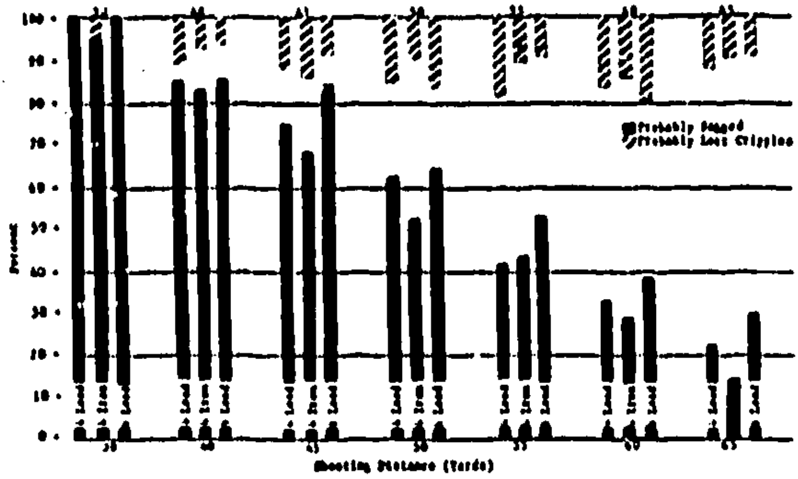
			Number 4 Lead					Number 4 Iron					Number 6 Lead				
Shooting Distance (Yards)	Total Ducks Shot	Sample for each Shot Type	Instant Kill*	1-5 Minutes	5 Minutes - 1 Day	1-10 Days	Survivors	Instant Kill*	1-5 Minutes	5 Minutes - 1 Day	1-10 Days	Survivors	Instant Kill*	1-5 Minutes	5 Minutes - 1 Day	1-10 Days	Survivors
Broadside																	
30	60	20	95	5	0	0	0	90	0	10	0	0	95	5	0	0	0
40	300	100	66	9	17	0	8	69	2	11	5	13	71	2	13	3	11
45	300	100	52	12	12	5	19	36	16	14	5	29	33	14	16	3	34
50	300	100	38	11	13	7	31	34	3	6	6	51	44	5	16	8	27
55	300	100	21	8	15	6	50	16	8	3	5	68	24	4	7	5	60
60	150	50	18	6	20	0	56	12	6	10	2	70	24	10	16	2	48
65	300	100	6	4	8	3	79	4	2	4	4	86	13	2	10	0	75
Head-on																	
40	150	50	46	6	22	4	22	48	8	6	4	34	48	20	22	0	10
50	150	50	20	8	16	2	54	14	10	14	2	60	8	8	12	4	68

* Death within 1 minute.

These categories also fail to take account of the probable fate of ducks with broken wings. Bellrose (1953) noted that ". . . the fracturing of a wing bone was the most important single type of wound resulting in the bagging of ducks."

Therefore, in Table 2, all ducks which died within 5 minutes plus those with at least one broken wing bone are grouped as "probably bagged." Those without broken wings are considered "lost cripples" if they died between 5 minutes and 10 days after shooting, and "survivors" if in apparent good health after 10 days. Figure 1 compares the performances of the three shot types at all broadside ranges.

Figure 1—Percentages of ducks probably "bagged" or "crippled and lost" as a result of shooting with three shot types at broadside distances of 30-65 yards



Statistical evaluation of the three tests, by analysis of variance, failed to establish differences at the 5 percent level of significance between the performance of Number 4 iron shot and Number 4 lead shot, either in terms of ducks "probably bagged" or ducks "crippled and lost." Shooting distance provided the only highly significant effect on the percentages of ducks "probably bagged" ($P=.01$). There were no discernible differences in vulnerability between hens and drakes.

TABLE 2.—PERCENTAGES OF DUCKS BAGGED BY THREE SHOT TYPES WITH ADJUSTMENT FOR WING BREAKAGE.

Shooting Distance (Yards)	Sample Size for each Shot Type	Percentage of ducks bagged, based on death within 5 minutes			Percentage of ducks with a broken wing			Percentage of ducks with broken wing and alive after 5 minutes			Percentage of ducks bagged, based on death within 5 minutes or broken wing		
		#4 Lead	#4 Iron	#6 Lead	#4 Lead	#4 Iron	#6 Lead	#4 Lead	#4 Iron	#6 Lead	#4 Lead	#4 Iron	#6 Lead
Broadside													
30	20	100	90	100	80	75	85	0	5	0	100	95	100
40	100	75	71	73	47	49	57	10	12	12	85	83	86
45	100	64	52	67	33	38	47	11	16	17	75	68	84
50	100	49	37	49	25	22	26	13	15	14	62	52	63
55	100	29	24	28	15	22	28	11	19	24	41	43	52
60	50	24	18	34	12	12	12	8	10	4	32	28	38
65	100	10	6	15	12	8	15	12	8	14	22	14	29
Head-on													
40	50	52	56	68	48	64	76	34	30	24	86	86	92
50	50	28	24	16	42	38	50	22	26	40	50	50	56

DISCUSSION

Ballistic studies have shown that the lower pellet weight of iron shot would result in a higher deceleration rate that cannot be overcome by raising muzzle velocity (Baker, 1966). Since the low-density iron shot lose energy more rapidly, it has always been assumed that they were less effective at longer ranges. This assumption has been based on the fact that a pellet needs sufficient energy to penetrate a vital area of the duck. This is obviously true, but the required threshold seems to be much lower than has been assumed. Our tests showed that the killing effectiveness of this soft iron shot was greater than anticipated.

The same reasoning has led to the assumption that at longer ranges Number 4 lead shot was more effective than the smaller Number 6 lead shot. Bellrose (1953) noted that Number 4 shot became increasingly more effective than Number 6 shot as ranges increased beyond 35 yards and attributed the superiority to a greater striking force. Our tests indicated that Number 6 lead shot was slightly more effective in bagging ducks than either type of Number 4 shot ($P = .05$). This apparent superiority of the Number 6 lead loads probably resulted because the greater number of pellets per load increased the probability of at least one pellet striking a vital area.

Our study failed to indicate that Number 4 lead shot would bag mallard ducks more effectively than Number 4 iron shot. Although the percentages of ducks "probably bagged" were numerically slightly higher for the lead shot in broadside shooting for six of seven distances (Figure 1), such an event would be expected more than 12 percent of the time by chance alone if the sho[illegible] were in fact identical. In head-on shooting at ranges of [illegible] yards, the performances of the two Number 4 shot loa[illegible] ually equal (Table 2).

Some have surmised that iron shot would res[illegible]ater loss of unretrieved cripples. The Nilo Farms test cond[illegible] the Mississippi Flyway Council (1965) suggested that on [illegible] contrary, crippling loss would actually be less with iron shot. Our tests indicated that the use of iron shot did not increase or decrease crippling loss.

The probability of bagging a duck, as defined in this test, is a function of range for any given shot type. In other words, the pattern density and, therefore, the probability of a shot pellet striking a vital area on the duck, decreases as range increases. In our test, the likelihood of "bagging" a perfectly centered duck decreased to less than 50 percent as range increased beyond 50 yards. This supports the frequently voiced admonition to duck hunters: "Let them come close before you shoot."

The killing effectiveness of the soft iron shot used in this test provides some hope for an eventual solution to the lead poisoning problem in waterfowl. Unfortunately, there are some major obstacles to be surmounted before a transition to iron shot is possible. The soft iron shot used in this test was produced by industry on a laboratory basis that was slow, costly, and totally unsuitable for large-scale production. No economic process for the manufacture of soft iron shot is now known. SAAMI is sponsoring the development of such a process by IIT and is also exploring other approaches to the problem. Even after a process has been found, the construction of facilities, procurement of equipment, and other matters will remain before iron shot becomes available for loading.

Summary

A cooperative research effort between the ammunition industry and the Bureau of Sport Fisheries and Wildlife is aimed at finding a suitable non-toxic substitute for lead shot. A contract study by an independent research organization evaluated ways of coating or detoxifying lead shot or replacing it with another metal. As a result of that study, the only promising candidate is soft iron. Previous tests of hard iron shot had suggested that its killing effectiveness was poor at longer ranges due to the lower density. In addition, its hardness caused excessive damage to shotgun barrels

A unique, automated shooting facility was constructed at the Patuxent Wildlife Research Center to test the killing effectiveness of soft iron shot under controlled conditions. Tethered game-farm mallards were transported across a shooting point in a manner simulating free flight. A microswitch triggered a mounted shotgun so that each shot was "perfect." A soft iron shot, in Number 4 size, was produced by the ammunition industry and loaded in 12-gauge shells to give optimum ballistic performance. Commercial loads of lead shot in both Number 4 and Number 6 size were used for comparison. A total of 2,010 ducks were shot at ranges of 30 to 65 yards and at broadside and head-on angles in a statistically designed procedure. The following data were recorded for each duck: time until death, broken wing or leg bones, and number of embedded shot. Those ducks not killed outright were held for 10 days. From these data, ducks were categorized as "probably bagged," "probably lost cripples," or survivors.

The test revealed [illegible] the killing effectiveness of this soft iron shot was superior to its anti[illegible]ed performance and close to that obtained with commercial lead [illegible] [illegible]taining an equal number of pellets. Bagging a duck, in [illegible] [illegible] death or broken wing, was primarily dependent [illegible] [illegible]ability of a shot striking that vital

area, and therefore a function of range. There was no indication that iron shot would result in greater crippling loss.

Despite the apparent effectiveness of this iron shot, transition to its use in waterfowl hunting is not now possible. The sample used for this test was produced by a laboratory procedure that is unsuitable for manufacture. There is no process for producing soft iron shot in the quantities needed. Industry is doing its best to resolve this problem.

ACKNOWLEDGMENTS

The assistance of many individuals contributed to the accomplishment of this work. The equipment and advice provided by members of the SAAMI non-toxic shot committee were essential to its success. Mr. Robert C. Heath, biometrician of the Patuxent Wildlife Research Center, Bureau of Sport Fisheries and Wildlife, provided guidance in designing the test procedure and analyzed the results.

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DISCUSSION

MR. TOM EVANS (Illinois): *Are you in a position to say what the industry appraisal of the effectiveness is? Do you feel that there is enough information with regard to iron shot that they might be inclined to accept it if a suitable means of manufacture could be found?*

MR. ANDREWS: The last part of your question is the big problem—a suitable means of manufacture. The sporting arms and ammunition manufacturers are studying the results of our tests in mathematical models. We hope we can test iron shot of other sizes and gauges and perhaps from that determine what the iron shot performance would be in other than the No. 4 load that we tested.